

# Landscape Analysis Application of the Westwide Pine Beetle FVS Extension

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**Abstract**—Landscape level analyses of forest management projects are necessary to consider many of the relevant future conditions and project impacts. Applications of FVS to landscape analyses are often hindered by incomplete inventory coverage of the landscape and the difficulty of representing and modeling spatial interactions between stands. The Westwide Pine Beetle (WWPB) extension to FVS operates on a multistand basis using the Parallel Processor Extension (PPE). The WWPB model simulates interactions of bark beetles and stand characteristics both within stands and among stands within a multistand landscape. To illustrate its functions, results are presented from an application of the WWPB model to a proposed forest management project on the Piney Analysis Area, Holy Cross Ranger District, White River National Forest, Colorado. The problems encountered in this application, such as data availability, and approaches for addressing them, are presented. Outputs from the simulation include both stand and landscape level displays. Stand results display projected tree mortality and stand structure changes as a function of stand composition and beetle outbreak intensity. Landscape outputs include both summary tables and ArcView-based map displays. Effects of stand management are shown both at the stand and landscape levels.

## Forestry in Time and Space

In the past, forestry concentrated on tree growth over time, using the stand as its basic unit of analysis. Spatial analysis tools were not needed as long as growth and yield was the major concern. However, over the past 20 years, concern for spatial relationships between stands, and the spatial relationship of stand management treatments, has emerged. Wildlife ecologists and others have concentrated on spatial relationships but have employed few temporally dynamic tools.

As with other forms of wildlife, bark beetles move between stands, and the population dynamics of these beetles encompass landscapes that include hundreds to thousands of

stands. In environments where pine bark beetles have a significant role in shaping forest structure, a stand-level approach to modeling their impact and response to management is inadequate. The likely future impact of pine bark beetles on a single stand depends on whether it is surrounded by a landscape of forests suitable or not suitable as beetle habitat. The Parallel Processor Extension (PPE) (Crookston and Stage 1991) of the Forest Vegetation Simulator (FVS) was developed to consider the spatial interactions between adjacent stands. The Westwide Pine Beetle extension employs PPE for its ability to model stand interactions and to consider the spatial distances between stands. The availability of Geographic Information Systems (GIS) has also been a key factor in the feasibility of landscape analysis. Not only do these systems allow easy storage and display of spatial data, they incorporate powerful spatial analysis routines needed for landscape analysis.

In this paper, we provide examples of how the Westwide Pine Beetle model (WWPB; Beukema and others 1997; FHTET in press)—a landscape-scale extension of the FVS—can be a useful tool in performing landscape analyses. These results illustrate the types of questions that may be addressed by the model and demonstrate features of model behavior.

## Scales and Complexity in Landscape Analyses

Landscape analyses can be conducted at a number of different spatial and/or temporal scales. An analysis ought to reflect the scale at which the model processes occur and address analysis-specific questions.

We categorize these scales of landscape analysis into five “levels” (table 1). These levels increase in complexity and each relate to a different “category” of analysis-related questions.

The first two levels are “nonspatial” in the sense that the physical location of the units of the landscape is not accounted for. Level 1 of landscape analysis considers the *aggregate conditions* of the stands in the landscape. For example, estimating landscape average host basal area per acre might suggest a landscape’s susceptibility to a bark beetle epidemic.

Level 2 considers average stand characteristics for *subsets* of the stands in the landscape, grouped, for example, by cover type or structural stage. Characterization by subsets of stands can provide information describing how *heterogeneous* a landscape is. Although these simple landscape analyses do not consider spatial relationships between the

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**Table 1**—Levels of landscape analysis.

Increasing level of complexity Level	Example type of analysis	Addresses questions and issues pertaining to
1	Summary statistics about landscape conditions	Average conditions
2	Analysis of landscape by stand condition classes (e.g. proportion of landscape in each class)	Homogeneity Heterogeneity
3	Analysis of the spatial distribution of the stand condition classes; this possibly gives rise to the creation of new condition class units ("emergent units"), via the aggregation of stand level units	Connectivity Fragmentation
4	Analysis of spatial arrangement of emergent condition class units	Edge/Configuration
5	Location within natural and cultural environment	"Place"

stands, they do provide a summary at a spatial scale "above" that of individual stand-level analyses. Such a landscape analysis could prove to be more relevant than stand-level analyses. For example, a stand that would have a high hazard rating for beetle attack in a single-stand analysis might be viewed differently if it was analyzed in the context of an otherwise low hazard landscape.

Level 3—the simplest analysis using spatial data—considers the size distribution of contiguous conditions within a landscape. This kind of analysis provides *fragmentation* and *connectivity* statistics. For example, after categorizing stands in a landscape according to some bark beetle risk rating system, one could "coalesce" adjacent stands of similar ranking into new units. The size distribution of these new units of similar risk could provide insight, for example, into the relative effectiveness of treatment alternatives to preserve unfragmented areas of wildlife habitat when faced with tree mortality from beetle outbreaks.

Level 4 considers the *spatial relationships* among different conditions and can provide information about distance between units, spatial patterns among units, amount of edge within and among units, and so forth. Continuing from the example above, one could analyze whether moderate risk units are *near* high risk units or *share substantial edge* with high risk units — findings that may have ecological significance. This more complex level of analysis—attained when the relationships of all stands (or other landscape units) are considered as elements of a landscape—may reveal ecologically important patterns and relationships that might otherwise be overlooked.

Even the most complex landscape analyses often stop at this fourth level. A level 5, however, is also possible, in which the location (or "place") of stands or groups of stands within a particular natural and cultural environment. Two different landscapes, for example, can be essentially alike in terms of the trees they contain, but if one of them represents critical habitat for an endangered animal species or a valued scenic resource to an urban population center, the importance placed on these places requires an analysis of these specific places in the landscape. Landscape averages or

aggregate indices are not adequate if they do not give specific information about these specific places.

## Input Data Considerations in Landscape Modeling

The techniques and models for spatial and landscape analysis developed over the past two decades have grown increasingly sophisticated and complex (Sklar and Costanza 1991). These tools are not often employed in forestry, however. One of the reasons for this nonuse is that it can be difficult to directly relate the results of the analyses to management goals. For example, an analysis of habitat fragmentation can rarely be used to accurately predict future species population levels. Perhaps more important is the problem of data quality and quantity. Stand-level inventories used as input data for FVS are not often available for large, contiguous forest areas. For landscape applications of FVS, lack of "wall-to-wall" stand data will remain a significant challenge for most users.

Meaningful landscape analyses can, however, still be performed even without comprehensive inventories. Imprecision resulting from incomplete input data can be mitigated in various ways. Even if complete stand inventories do not exist, some information is generally available for the forested areas in the landscape. This information can be used through imputation techniques to fill in these areas with tree lists from inventoried stands. In our analyses, some portions of the landscape were occupied by tree species that are not susceptible to pine beetles. For areas of aspen (*Populus tremuloides* Michx.) stands in the landscape, for example, it was not too important to know precisely the structure of these stands. In other cases, areas were known to have been recently clearcut and regenerated with lodgepole pine (*Pinus contorta* Douglas var. *latifolia* Engelm.). Simulation alternatives that thin stands to a target density eliminate some of the uncertainty, because postthinned conditions can be assumed to be close to the management prescription. Stands with average size and stocking conditions for regeneration units of this age were assigned to these areas. These trees will not be of sufficient size to be

attacked by pine bark beetles during the projection period, so more precise data are not needed. In some cases, more sophisticated imputation procedures could be employed to populate the landscape where stand data are missing (Moeur and Stage 1995).

Some times data will be missing from stands that are central to the analysis. For these areas, a sensitivity analysis approach can be used (Ruckelshaus and others 1997). In our example case, the sample stands that were simulated represent the range of stand conditions in the landscape, in the proportion they appeared in a sample inventory. The sample selected may underestimate the proportion of high hazard stands that actually exist in the landscape; in our case, highly stocked stands with higher proportions of larger diameter pine. To determine the sensitivity of the analysis to this source of sample error, the sample-based simulation results can be compared with those from a landscape populated by a higher (and lower) proportion of high hazard stands.

Finally, some portions of the analysis area are likely to be of more interest than others. For example, stands in a specific location may be important components of wildlife habitat, but stand inventories may not be available for all the stands in this area. Again, a sensitivity analysis may be used to determine if simulated future habitat conditions in this area are sensitive to the assumption that sampled conditions also represent the unsampled conditions. If so, then it may be possible to gather additional data in areas where the simulation results are critical to decisions.

In all cases, one must remember to treat simulation model results as imperfect summaries of present and future conditions. Stand inventory data are only samples of what actually exists, and FVS and the WWPB extension are only statistical tools and abstractions of reality.

## Westwide Pine Beetle Model

As an extension to the FVS—in conjunction with PPE—the WWPB model simulates between-stand bark beetle contagion processes across a landscape, as well as within-stand growth and mortality processes (FHTET, in press). The importance of landscape-level mountain pine beetle (MPB; *Dendroctonus ponderosae* Hopkins) populations has been recognized as significant in determining risk at the stand level (Shore and Safranyik 1992). The model is capable of simulating the effects of three beetle species: the mountain pine beetle, the western pine beetle (WPB; *Dendroctonus brevicornis* LeConte), and *Ips* species. Our example applications simulate MPB in lodgepole pine.

Beetle populations per se are not simulated. Instead, beetles are represented in terms of “Beetle Kill Potential” or BKP. One unit of BKP represents an amount of beetles able to kill 1 square foot of basal area. BKP is allocated to and from stands annually. The amount of BKP allocated among stands is a function of the amount of BKP present in each stand, stand conditions in both the donor and recipient stands, and the distance between donor and recipient stands. Once allocated to a stand, BKP is assigned to specific tree size classes based on stand conditions. With sufficient BKP, trees are simulated as being killed. The amount of BKP in

the following year is primarily a function of the diameters and numbers of trees that were killed the previous year.

Three spatial scales exist within the WWPB model:

1. Individual forest stands.
2. The collection of stands that compose the landscape.
3. A larger area (outside of, and encompassing, the landscape) referred to as the “outside world,” which serves as a “source” and “sink” for landscape BKP.

The spatial relationships of stands within the landscape are explicitly considered. Being a landscape-scale model, the WWPB model is designed primarily to evaluate scenarios at the **landscape** scale. That is, it can be used to address questions such as:

- What *proportion* of a landscape might experience severe beetle mortality (given a specific outbreak scenario)?
- What *types* of stands are most vulnerable to beetle attack?
- If certain areas experience an outbreak, how quickly—and how far—might an outbreak spread?
- How might specific management actions affect future beetle dynamics?

At the **stand** level, the model may be used to address questions such as:

- How will a severe bark beetle outbreak affect stand structure?
- How long might stands experience high levels of beetles?
- What levels of mortality might some stands experience?

Note that these stand-level questions are posed in a general way. The model is *not* designed to predict precisely *which* individual stands in a landscape *will be* attacked or impacted by bark beetles. Rather, the model is designed to provide insight as to what *kinds* of stands in this landscape might experience beetle mortality, and how much mortality might occur. This can be simulated for different management and outbreak scenarios. In other words, although the *grain* of the WWPB model involves stands, its *extent* is the landscape, and that is the scale at which interpretation of output is most meaningful. To the degree that the spatial arrangement of stands in the landscape is known, some spatial information is inherent in the model results. For example, areas in the landscape that do not have host trees will not experience mortality.

## Objectives and Dimensions of this Analysis

The objectives for this analysis are to use the WWPB model to help address the following questions:

- How will MPB outbreaks of varying intensity affect the landscape (defined below) as a whole?
- How will outbreaks of varying intensity affect the component stands?
- How will beetle-induced mortality manifest itself temporally and spatially across the landscape?
- How will specific management actions affect bark beetle dynamics?

We addressed these questions by organizing our simulations and analyses around the following *dimensions* of analysis.

- Distribution of stands within the landscape
- Time (as it affects growth and mortality)
- Treatments (thinnings)
- Outbreak intensity scenarios
- Stand-level responses and conditions
- Landscape conditions

A thorough discussion of all of these dimensions is beyond the scope of this paper. We address the first four dimensions—which are especially relevant during the simulation set-up phase of the analysis—only in a cursory way. This paper focuses primarily on the last two dimensions of the analysis: stand-level and landscape-level responses to the MPB, as projected by the WWPB Model.

## Methods

Our analysis addresses a 23,000-acre landscape in the Piney Analysis Area, Holy Cross Ranger District, White River National Forest in Colorado. This area was the subject of a previous forest health assessment that used the single stand Mountain Pine Beetle FVS extension to analyze the possible impact of this insect on selected stands (Angwin and others 1996). Sources of information used for imputing stand information and setting up the simulation included:

- Recent stage 2 stand inventories for the area
- Digital cover type maps for the area
- Maps of past treatment areas
- Known proposed treatments and treatment areas
- Knowledge of current beetle conditions and likely outbreak dynamics
- Online Vail, CO, climate information (to provide insight into the frequency, duration, and magnitude of stress events)

Lodgepole pine is the primary species (percent of total stand basal area in host ranged from 66 to 100 percent), with additional components of subalpine fir (*Abies lasiocarpa* (Hook.) Nutt.), Engelmann spruce (*Picea engelmannii* Parry ex Engelm.), and aspen. Stand basal areas ranged from 48 to 232 square feet per acre; quadratic mean diameters (Q.M.D.) ranged from 2.6 to 14.2 inches. The area has experienced recent MPB activity.

Because digital stand maps were not available, we subdivided the landscape into 221 “stands,” each 0.6 km by 0.7 km (approximately 100 acres). Using digital vegetation-type maps and hand-drawn district stand maps, we estimated the actual percent of the landscape stocked to host pine types, and the locations (in our simulated landscape) for proposed silvicultural treatments and previous clearcuts. We populated the stands with treelists from 19 representative stand inventories in such a way as to maintain a quantitatively accurate distribution of cover type, basal area distribution, and MPB risk rating across the landscape (spatial accuracy was also maintained for cover type). “Replicating” inventories in the landscape served two purposes: it facilitated analyzing the effect of stand location on beetle

dynamics, and it “filled in” the landscape to account for uninventoried stands.

BKP was initialized in the simulated landscape at low (endemic) levels. Under base case conditions for this landscape, the WWPB model projects gradually increasing endemic mortality over a 20-year period. One of the features of the model is that “stress events,” which can simulate conditions such as droughts, can be imposed. These events cause tree resistance to bark beetles to decline. Events were simulated to create MPB outbreaks of two intensities: one designated as a “severe” outbreak, another designated as a “moderate” outbreak. The stress event variable (field 3 of VARYRAIN keyword) has a default value of zero; it can be changed to be positive or negative. When it is set to be positive, tree vigor is increased and resistance to beetle attacks is increased. This approach was used to create outbreak scenarios that collapsed in realistic fashion.

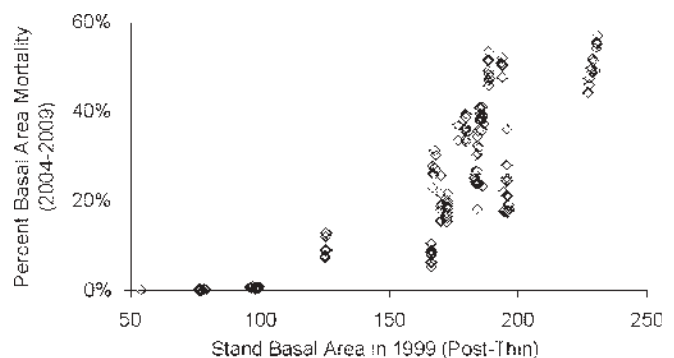
Simulated thinning alternatives were constructed based on actual management proposals for this site. Treatments were simulated as thins-from-below to a residual basal area of 80 or 100 square feet per acre. The base case for managed scenarios applied treatments to about 10 percent of the area.

Simulations were run for 30 years, beginning in inventory year 1994. Simulated MPB outbreaks commenced in 2004, triggered by the use of the VARYRAIN keyword.

## Results

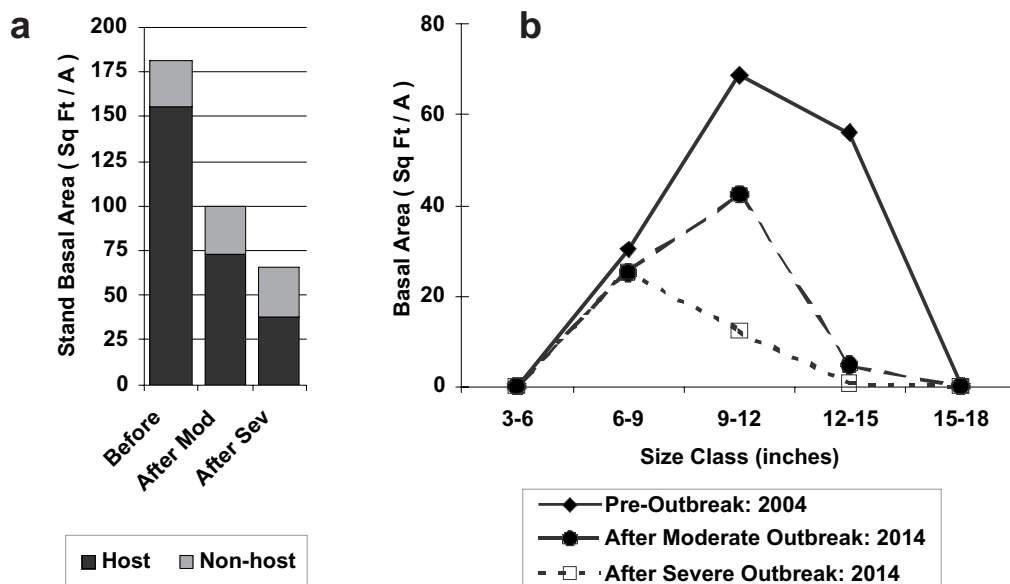
### Stand-Level Responses

Simulated MPB outbreaks differentially affected stands. During a simulated “severe” outbreak, mortality rates ranged from zero in the sparsest stands, to nearly 60 percent basal area mortality over 5 years in the densest stands, with an apparent “threshold” of somewhere between 100 and 120 square feet of basal area, below which only very low levels of mortality occurred (fig. 1). Host basal area mortality rates (10-year) sometimes exceeded 75 percent (fig. 2a). Peak 5-



**Figure 1**—Simulated beetle-induced mortality rates over 5 years (2004-2009) as a percentage of the preoutbreak (postthin) basal area. Each point represents one of the 163 simulated stands. Stands with 1999 basal areas of 80 and 100 sq ft per acre were thinned (from below) to these levels in 1999.



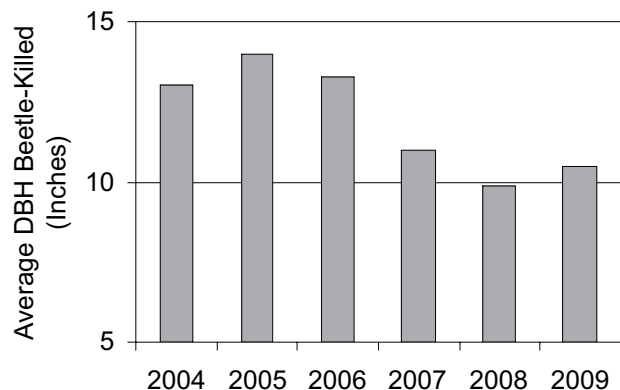


**Figure 2**—(a) Stand basal area by host and nonhost in 2004, and in 2014 after simulated “severe” and “moderate” MPB outbreaks for one stand in the landscape. (b) Basal area by tree size class for the same stand and time period as shown in (a).

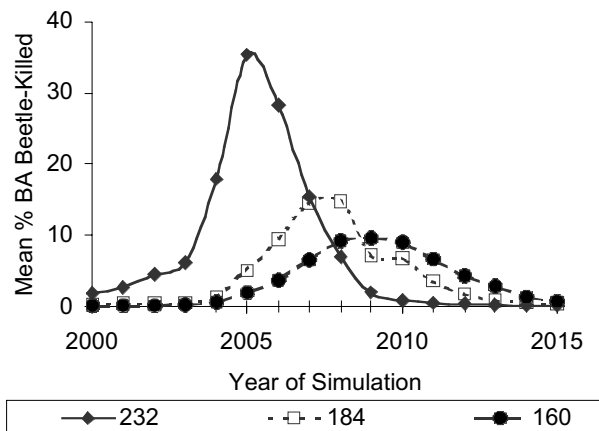
year percent basal area mortality was approximately 40 percent for the moderate outbreak (data not shown).

Within stands, beetle-caused mortality occurred primarily in the largest size classes for both severe and moderate outbreak scenarios (fig. 2b). Resulting stand structures after simulated outbreaks are noticeably different depending upon the severity of the outbreak. Over time, smaller size classes are attacked (fig. 3).

Within-stand temporal trajectories of beetle outbreak varied significantly, stand to stand (fig. 4). Generally, denser stands with larger trees experienced more rapid mortality rates, followed by a relatively rapid decline of BKP levels. Conversely, lower basal area stands with smaller Q.M.D. experienced BKP pressure later in the simulation and for longer periods, sometimes even well after the landscape-wide outbreak had subsided.



**Figure 3**—Landscape average diameter at breast height of beetle-killed trees by year during the simulated “severe” outbreak.

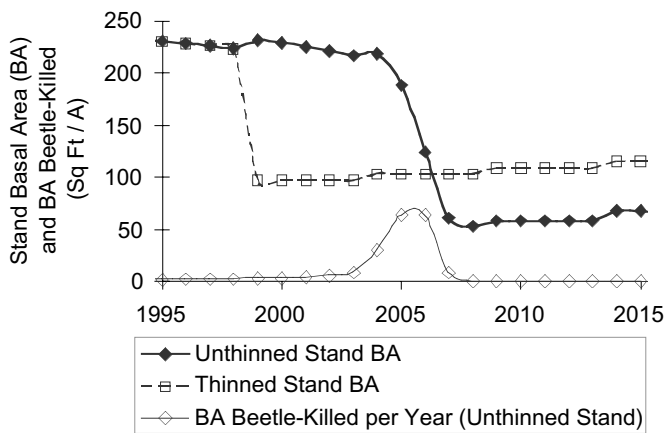


**Figure 4**—BKP levels for three stands during a simulated severe MPB outbreak. These “temporal trajectories” show how landscape-scale outbreaks manifest differently in different stands. Legend indicates each stand’s 1984 (beginning of simulation) basal area.

Thinned stands experienced little if any beetle-caused mortality (fig. 1 and 5). This thinning effect was observed in spite of stands having, after thinning, higher proportions of host and a larger host Q.M.D., characteristics that generally are attractive to beetles.

## Landscape-Level Responses

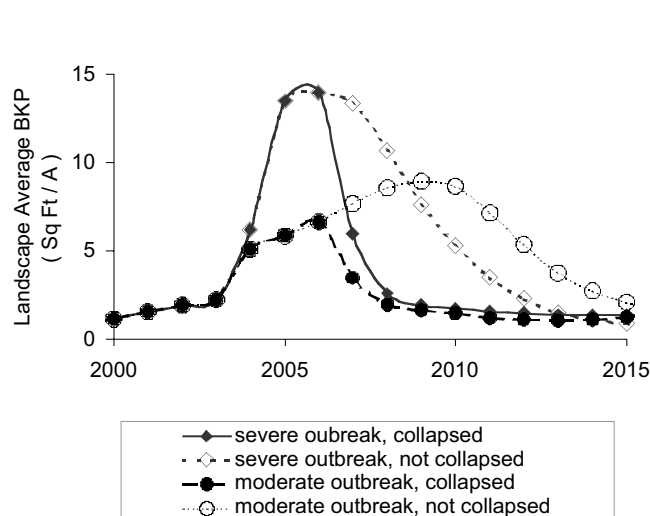
Simulated outbreaks took on different trajectories (landscape wide) depending upon how severe the outbreak was (how negative of VARYRAIN values were used and for how long), and how intensely the outbreak was “collapsed” (how



**Figure 5**—Stand basal area for two “replicate” stands, identical at the beginning of the simulation, during the severe outbreak simulation. One was thinned in 1999. Beetle-induced basal area mortality (per year) also is shown for the unthinned stand.

positive of a VARYRAIN keyword was used). We present four scenarios: a severe outbreak, collapsed; a severe outbreak, not collapsed; a moderate outbreak, collapsed, and a moderate outbreak, not collapsed (fig. 6). The severe outbreak scenarios resulted in landscapewide BKP rate increases that were higher than in the moderate outbreak scenarios. Rates of BKP increase appears to be controlled more by the stress event or beetle dynamics rather than on the stand conditions per se. Uncollapsed outbreaks—which eventually subsided because relatively few adequate trees remained in the landscape (data not shown)—took about twice as long to subside (approximately 10 years) than did the collapsed simulations.

Figure 4, which represents outbreak trajectories for individual stands in the severe outbreak, collapsed scenario,



**Figure 6**—Landscape average BKP per acre over time for four simulation scenarios, showing that simulated outbreaks can have different temporal trajectories.

suggests a landscape scale phenomenon not revealed by the landscape-scale average graph (fig. 6). Although landscapewide the outbreak appears to have subsided by 2010, notice that some individual stands are just then attaining their peak BKP levels.

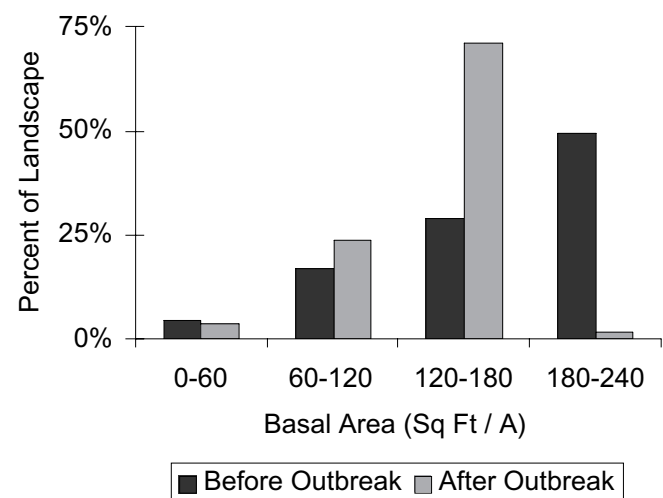
Distribution, landscapewide, of stand basal area per acre changes significantly after simulated outbreaks (fig. 7). This result follows from the individual stand phenomena suggested by figure 2b.

Figure 1 suggests the significance of stand location in the landscape. As discussed, tree inventories used to populate the stands in this landscape were replicated. Because replicates had similar stand basal area in 1999 (among themselves) before the simulated outbreaks, the difference in beetle mortality experienced by identical stands in different locations in the landscape is represented by the vertical range among the replicates, which appear together in vertical lines in the figure.

## Discussion

The review of the analysis presented here illustrates the following:

1. Through use of the PPE extension, FVS can be used to represent interstand contagion processes that occur over a large number of stands (at least a few hundred) and that may occur at time steps less than a typical FVS cycle.
2. Spatial processes that take place at a landscape scale cannot be reliably modeled at the stand level; the stand-level outcome can be affected by both the entire landscape conditions and the conditions immediately surrounding the stand.
3. The amount of meaningful analysis that can be performed on a landscape with FVS is limited by the amount of data available for the landscape and the validity of the models being employed; but through sensitivity analysis and use of imputed data, useful landscape projections and comparisons can still be made.



**Figure 7**—Frequency distribution of stand basal area classes landscapewide, before and after a simulated severe outbreak. (The sum of each of the two series equals 100 percent.)

Spatially explicit analyses can be performed on WWPB output by importing the results to a Geographic Information System such as ArcView®. Such analyses are not meaningful for this example because only the types of stands from the actual landscape, and not their spatial arrangement, are represented. Specific functions included in the WWPB software package facilitate moving output directly into ArcView®. FVS-EMAP (McMahan and others, this proceedings) is a flexible tool designed to perform this function for general FVS applications.

Though not presented here, GIS analyses can be used to describe the spatial effects of WWPB model outputs. A relatively simple procedure is to dissolve boundaries between stands with similar characteristics (such as cover type and age class) and display the distribution of sizes of these contiguous areas. A number of more sophisticated procedures have been developed and are routinely employed by landscape ecologists (O'Neill and others 1988; Turner 1990; Cullinan and Thomas 1992).

Several other multistand processes and conditions, including fire, wildlife habitat, and watershed hydrology, could be modeled with an approach similar to that used by WWPB. Such models, including WWPB, could be linked so that landscape impacts over time and space of landscape disturbances could be better understood and displayed.

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